Simulations Used as Experiments in Autonomous Mobile Robotics

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Abstract— **Autonomous mobile robotics has seen a recent effort for the development of good experimental methodologies that aim at providing more rigor to the experiments conducted in the field. Simulations are becoming increasingly important tools in experimental activities of autonomous mobile robotics, but, so far, they have not been at the very center of attention in the development of experimental methodologies. This paper tries to stimulate the discussion on some issues related to simulations and experiments, starting from the two following questions:**

- **what are simulations in autonomous mobile robotics?**
- **what is the role of simulations in autonomous mobile robotics?**

I. INTRODUCTION

Experiments are essential ingredients of science, playing a role both to confirm/refuse a theory and to find out new theories. If a rigorous experimental approach has proved to be crucial for natural sciences, it is reasonable to expect that it can be also useful in engineering, especially when the behavior of an artifact and its performance are difficult to characterize analytically, as it is often the case in robotics.

In this work, we concentrate on autonomous mobile robotics (to which we will often refer to as simply 'robotics'), namely on the discipline that aims at developing mobile robotic platforms that can operate without continuous human control in unpredictable environments, like mobile robots for planetary exploration and service robots for performing housework. It is widely recognized that, although their importance, experimental activities in autonomous mobile robotics are often carried out with low standards of methodological rigor. In this area, the term 'experiment' seems to usually denote a test made to show that a system works, or that it works better than other systems built for the same purpose. A critical analysis of the role of experiments in autonomous mobile robotics has recently taken place [1], [2], [3] and it is envisaged that, in the very next years, robotic engineers will exploit the valuable opportunity to come up with good experimental methodologies.

The purpose of this paper is to stimulate the discussion on some issues related to simulation that, so far, has not been at the very center of attention in the development of experimental methodologies for autonomous robots. In particular, we will attempt to answer the two following questions:

- what are simulations in autonomous mobile robotics?
- what is the role of simulations in autonomous mobile robotics?

Despite they might appear trivial at a first sight, we will show that the above questions involve non-trivial considerations, especially when considered at the light of some principles on which experimental methodologies should be based. An interesting point that we address is to show why and how simulations can be used as experiments in autonomous mobile robotics. We explicitly remark that our goal with this paper is to stimulate the community discussion on the above issues, hence we will not provide definitive answers but only our point of view on them.

This paper is structured as follows. The next section presents the general view on experiments in robotics from which we move. Sections III and IV constitute the core of the paper and discuss the nature and the role, respectively, of simulations in autonomous mobile robotics. Section V concludes the paper.

II. THE GENERAL VIEW

In this section, we summarize our general view on experimental methodologies in autonomous mobile robotics. A more complete discussion can be found in [4].

The starting point is reflecting on the nature of robotics that, in our opinion, is at the intersection between engineering and science. From the one hand, robotics appears more similar to engineering than to science, since differently from the objects of scientific investigation, robotic systems are artifacts built by humans and could not exist without human intervention [5]. According to this view, experiments in robotics have the goal of demonstrating that a given artifact is working or that it is better than another. From the other hand, the most advanced autonomous robotic systems are so complex that their behavior is hardly predictable, even by their own designers, especially when considering their interaction with the real world. In this perspective, experiments in robotics are somehow similar to experiments in natural sciences since, broadly speaking, both have the goal to understand how complex systems work.

According to this peculiar nature of robotics, we think that looking at the way experiments are conducted in natural science and in other engineering disciplines might be the first step to develop a good experimental methodology for autonomous mobile robotics.

Here, we report a number of experimental principles (from [4]) holding in science and that can be worth considering also in autonomous mobile robotics.

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- *Comparison*. At a higher level, comparison means to know what has been already done in the past within the same field of research, both for avoiding to repeat uninteresting experiments and for getting suggestions on what the interesting questions could be. At a lower level, comparison refers to the possibility for future researchers to accurately compare their new results with the old ones.
- *Reproducibility and repeatability*. (See also [6] for a discussion on this principle.) These features are often confused but, although tightly connected, they refer to different desiderata. They are related to the very general idea that scientic results should undergo to the most severe criticisms in order to be strongly confirmed. *Reproducibility* is the possibility to verify, in an independent way, the results of a given experiment. It refers to the fact that other experimenters, different from the one claiming for the validity of some results, are able to achieve the same results, by starting from the same initial conditions, using the same type of instruments, and adopting the same experimental techniques. As in the case of comparison, to be reproducible an experiment must be fully documented. *Repeatability* concerns the fact that a single result is not sufficient to ensure the success of an experiment. A successful experiment must be the outcome of a number of trials, performed at different times and in different places. These requirements guarantee that the result has not been achieved by chance, but is systematic.
- *Justification/explanation*. This principle deals with the drawing of well-justied conclusions on the basis of all the information collected during an experiment. In an experimental procedure, it is not sufficient to collect as much precise data as possible, but it is necessary to look for an explanation of these data. Therefore, not only the drawn conclusions must be strongly supported, but also all the experimental data should be interpreted in order to derive the correct implications.

In the last years, there has been a growing number of published papers in the field of autonomous mobile robotics that present experimental results based only on simulations, performed with tools like Player/Stage [7] and USARSim [8]. This fact triggers questions about the use of simulations as experiments in robotics. In the following of this paper, we address some of these questions, at the light of the conceptual framework introduced in this section. As a first step, we try to investigate the very idea of simulation in autonomous mobile robotics; then, we discuss the role of simulations in autonomous mobile robotics.

III. WHAT ARE SIMULATIONS IN AUTONOMOUS MOBILE ROBOTICS?

A. On the General Nature of Simulations

Generally speaking, a simulation imitates a process by another process [9]. We can say that a simulation reproduces the behavior of a system using another system and, in this sense, it is a *dynamic* representation of a portion of reality. We can identify two elements that are involved in a simulation: a model that represents a portion of reality and the execution of this model. Hence, we can say that *simulation = model + execution*.

From the above discussion, it emerges that simulations are closely related to dynamic models that include assumptions about the time-evolution of a system. However, we believe that simulations represent reality in a different way than models do, as evidenced by the following example. Let us consider a scale physical model of a bridge that is going to be constructed. This is a representation that replicates some features of the real object (the bridge that is going to be built) abstracting from the full details and concentrating on the aspects relevant to the purpose. For example, if the scale model has been constructed in order to show to its purchasers the final shape of the bridge, it would not be important its material, color, or dimension. What is represented in a model depends on the purposes for which the model has been conceived. Now let us consider the case in which the same scale model is build to test the resistance of some materials, used in construction, to some atmospheric agents. In this case, the sole model is not enough for the purpose of testing the resistance of these materials; the model has to be put in a (controlled) physical environment where it can be subjected to the action of the atmospheric conditions. Here, we see something more than a simple description of a portion of reality; in a sense, the model is *executed* in the reality by means of the action performed by the environment: this is what we call a *simulation*. As the example shows, in order to have a simulation, it is necessary both to have a model and to execute it. Simulation involves more than a (static) model as it requires that the model is evolved to mimic the corresponding evolution that takes place in reality. The execution of a model to have a simulation is performed by an “agent” that can be the reality itself, as in the case of the bridge or, much more frequently, a computer.

The difference between model and simulation, and between representation and execution, considered above is probably better evidenced in the case of computer simulations, which are based on *computational models*, namely formal mechanisms able to manipulate strings of symbols, that is to compute functions. The difference between model and simulation is tightly connected to that between a program and a process. Actually a completely specified computational model defines a program (as a sequence of operations), whereas the process resulting from the execution of a computational model, representing the behavior of a system, is a simulation process executed by a computer. It is important to notice that not every execution of a computational model is a simulation. To have a simulation, we need computational models that represent a system behavior whose state changes in time. Moreover, it is worth stressing that without an underlying model (that represents the system) a simulation cannot occur and, at the same time, that a simulation is not just a representation, but an *executable* representation.

B. Simulations in Autonomous Mobile Robotics

As we have seen, a simulation needs a dynamic model of the system it reproduces. In the case of autonomous mobile robotics, the system that is reproduced is a mobile robot that acts in an environment. The dynamic model must therefore include a representation of the robot and a representation of its interaction with the environment. Let us detail the elements comprised in these two representations. Roughly speaking, a mobile robot is modeled by representing its locomotion, sensing, and control subsystems (a program that determines the next action of the robot on the basis of the past history of perceptions and actions). The interaction of a mobile robot with an environment is a complex issue. For example, it involves a model describing the behavior of the robot in the environment after the control subsystem issued a command. If the command is 'go forward 50 cm', the actual movement of a wheeled robot in a real environment could be more or less than half a meter because of slipping wheels, of rough terrain, of errors in the motors moving the wheels, and of several other reasons. It is not easy to capture this variability in a computational model. Similar problems emerge in modeling the perception of the robot in the environment. Current robotic simulations model in different ways the uncertainties on the effects of actions and on the perceptions. The first kind of uncertainty is usually managed by the physical engine (see below), while the second kind of uncertainty is artificially added to the data, according to different probability distributions.

Autonomy makes modeling a robot's interaction with the environment even more complicated, because interactions are hardly predictable. This is probably one of the reasons for the late adoption of simulation in autonomous mobile robotics. Until few years ago, the models of interaction between robots and the world were not enough accurate and using simulations based on these models was simply not convenient for the autonomous mobile robotic community. If a simulation is based on inaccurate models of the interaction with the world, it is not representative of the behavior of real autonomous robots and, as such, cannot be used to validate the behavior of the simulated robots and to generalize it to real robots. Nowadays, one of the most used simulators for autonomous mobile robots, USARSim [8], models the interaction of robots with environment using a software, called Unreal engine, initially developed for a multiplayer combat-oriented first-person shooter computer game, Unreal Tournament 2004. Unreal engine contains a physics engine that simulates the interaction of three-dimensional physical objects and that allows to obtain highly realistic simulations. Resorting to components developed in the extremely competitive field of computer games is an interesting way to have state-of-the-art models of physical interaction between objects.

In discussing the nature of simulations in autonomous mobile robotics, it is interesting to mention a trend that is emerging in the last years: the use of publicly available data sets composed of data collected in the real world by some researchers [10], [11]. These data sets substitute sensor data in experimental tests of robotic systems. From the one hand, we can think of these data sets as models of the interaction between the robots and the real environment. Using these data sets appears very similar to perform a simulation, in which the underlying model is very precise, because it exactly records the interaction of real robots with real world. According to this view, the difficulty of building a model of the perception of a robot in an environment is addressed by letting the data collected during real operations be the model. From the other hand, using publicly available data sets can be considered as a real (not simulated) experiment, in which activities of collecting and processing data are performed in different places at different times. What is emerging here is a sort of continuum, ranging from performing completely simulated experiments, to using data sets like [10], [11], to performing real-world experiments.

IV. WHAT IS THE ROLE OF SIMULATIONS IN AUTONOMOUS MOBILE ROBOTICS?

We now discuss the role of simulations in developing experimental methodologies for autonomous mobile robotics. In our opinion, a good way to address the relationship between simulations and experiments is to say that simulations *can be used* as experiments. The relation between simulations and experiments have been debated from several years within philosophy of science with a variety of positions. Here we report just a small sample of these positions to give the flavor of the discussion. Simulations have been considered as techniques for conducting experiments on digital computers [12], as substitutes for experiments that are impossible to make in reality [9], or as special kinds of experiments [13]. In our view, a simulation *per se* is not an experiment; for example, think of a flight simulation used for training purposes. However, a simulation can be part of an experiment; for example, think of a simulation of a protein process folding used in an experiment for studying some gene.

Simulations seem more common in some areas of robotics and less common in other areas. For instance, in the area of locomotion of legged robots, simulations are widely used to validate design choices. This might be due to the fact that there exist very good models (both cinematic and dynamic) of the behavior of robotic legs in a given situation (terrain, friction, forces, . . .). On the other hand, in the area of robotic vision, simulations are employed less frequently, probably because of the lack of good models of the behavior of cameras in a given situation (lights, shadows, . . .). Autonomous mobile robotics seems to be in an intermediate position, as good models of the behavior of a mobile robot in an environment are appearing (as discussed above) and, consequently, simulations are being increasingly employed. Using computer simulations has a potential impact on a number of issues that are relevant in the definition of good experimental methodologies for autonomous mobile robots. Let us comment on this impact with respect to the issues listed in Section II. We explicitly remark that several of the issues discussed below are highly interconnected and are inserted in a structured scheme only for presentation purposes.

- *Comparison*. Using simulations makes the creation of a common ground for comparing the performance of different systems easier. Simulations represent much more controlled settings than real world. For example, two systems for planning a path that brings a robot from a start pose (namely, from starting position and orientation, according to some reference frame) to a destination pose avoiding collisions with obstacles [14] should be compared in the same environments. To fairly compare the two systems, the shape, size, and position of obstacles in the environment are critical. The same environments can be reproduced in reality with much more difficulty than in simulation.

  Moreover, simulations allow to access a large number of measurable parameters (e.g., computational time, memory usage, precision, and accuracy) that can be used for comparison purposes. It is important to remark that, using a standard simulation tool, like Player/Stage [7], these parameters are measured in a uniform way over different runs of the simulation, which may be performed at different times and in different places. In this sense, simulations, being very controlled settings in which parameters can be accurately set and measured, allows to investigate more precisely the reasons for different performance of competing robotic systems.

  Generally speaking, as discussed in [15], there are three ways to compare performance of algorithms, in decreasing order of appeal:

  1) use the same code that was used in the previous experiments,
  2) develop a comparable implementation, starting from the description provided in papers and reports,
  3) compare the results with those obtained in other papers.

  From the current state of the art in autonomous mobile robotics [4], most comparisons are presently conducted adopting the second way. The availability of standard simulation tools helps in moving toward the first way of comparison, because they ease the process of writing code and push researchers to make their code available, as in the OpenSLAM initiative [16].

  The recent interest in developing benchmarks for autonomous mobile robotics, to assess the relative performance of robotic systems by running a number of standard tests, is an aspect of interest in the context of comparison. Proposed benchmarks [10] are based on publicly available data sets that, as discussed above, can be considered somewhere between simulations and real experiments. Benchmarks can be of two types [10]:

  > Benchmark Problems (BPs), defined as the union of: (i) the detailed and unambiguous description of a task; (ii) a collection of raw multisensor data, gathered through experimental activity, to be used as the input for the execution of the task; (iii) a set of rating methodologies for the evaluation of the results of the task execution. The application of the given methodologies to the output of an algorithm or piece of software designed to solve a Benchmark Problem produces a set of scores that can be used to assess the performance of the algorithm or compare it with other algorithms.
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  > Benchmark Solutions (BSs), defined as the union of: (i) a BP; (ii) the detailed description of an algorithm for the solution of the BP (possibly including the source code of its implementation and/or executable code); (iii) the complete output of the algorithm when applied to the BP; (iv) the scores associated to this output, calculated with the methodology specified in the BP.

  Sometimes, comparison of robotic systems is done in simulated competitions [17]. For example, in the RoboCup Rescue Simulation League, robotic systems for search and rescue in large scale disaster situations are simulated using USARSim. Beyond assessing performance in the specific applications, simulated competitions are also sought to foster research on advanced and interdisciplinary topics; for example, search and rescue involve engineering, medical, logistic, and social problems.
- *Reproducibility and repeatability*. Arguably, the major impact of simulations on experimental practice of autonomous mobile robotics is on reproducibility and repeatability. In particular, being the setting up of simulations much more easier than the setting up of real robotic experiments (e.g., think of the hardware failures and of battery recharges), use of simulations is expected facilitate both repeating the same experiment and reproducing the same conclusions. For example, several environments (indoor offices, indoor open spaces, outdoor crowded streets, outdoor parking lots, . . .) can be considered without much effort during the testing of a simulated system. USARSim comes with a dozen of already available maps, in which autonomous mobile robotic systems can be tested.
- *Justification/explanation*. One of the techniques used to derive well-justified conclusions from experiments is to test a system in different settings (different environments, different parameter configuration). Simulation environments offer a way to easily change from a setting to another one and to provide robust results, that can be verified according to *ground truth*, namely to “real” results. For example, a robotic system for building maps of unknown environments can be simulated and the produced maps (representations of the obstacles and the free space build by the robot) can be compared with ground truth maps (representations of the obstacles and the free space available in the simulator) for evaluating their quality and, as a consequence, the quality of the

mapping system. Ground truth is trivially available for simulated environments but it is seldom available for real environments (sometimes aerial images and Google Earth maps are considered as ground truth for real outdoor environments).

The use of simulations in experimental activities related to autonomous mobile robots involves also a number of problematic issues, including the following.

- Validation of results. To what extent can we "trust" results coming from simulations? Some attempts to answer this question have been done [18], but more work is needed.
- Generalization of results. Can we generalize the results obtained via simulation to other settings and other robots?
- Use of simulations not based on computers. Is it reasonable to simulate a real robot by using a scale robot operating in a scale environment?

V. CONCLUSIONS

In this paper we have discussed the nature of simulations in autonomous mobile robotics and their role in the ongoing definition of good experimental methodologies. We think that this work can constitute a stimulus for reflecting and discussing about these issues.

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